THE WORLD OF CHEMISTRY

Program #16

THE PROTON IN CHEMISTRY

Producers Jack Arnold
and Matt Dibble

Air Script: October 31, 1988

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Annenberg/CPB Project Logo and Music

Funder Credits

MONTAGE: Archival commercial footage, rain, lab demo, archival photograph of Soren Sorenson, pH scale, chemical reactions, graphic

NARRATOR (MUSIC and NAT SOUND under):
Acid stomach, acid rain, acid in your drink? How to measure the relative strength of acids and bases. In 1909, Soren Sorenson, employed by a Danish brewery to measure normal acidity in beer, invented the pH scale. What is pH, and what, in the first place, are acids and bases? To find out, we must uncover the vital role of the proton in chemistry.

SUPER: THE PROTON IN CHEMISTRY

THE WORLD OF CHEMISTRY OPEN: Montage, Music, Logo

RH at chemical plant

ROALD HOFFMANN (SYNC):
Acid spills, acid rain. Acids have certainly been getting a bad press lately, and that on top of an intuition that we have that acids are destructive, corrosive. Does that reflect the reality of the position of acids and bases in our society? Not at all. There's a list of the top ten chemicals in the world. Number one on that list is a molecule made to the tune of 33 billion kilograms every year in the U.S. alone. And that's a strong acid, sulfuric acid. Among those top ten are no less than 5 acids and bases. The truth of the matter is that acids and bases are enormously beneficial. They are used in almost everything that's manufactured around us. For instance, here is a tank car of sulfuric acid. It's transformed here at Delta Chemical into aluminum sulfate that's used in the paper industry and in purifying water. Over there is a tank car of sodium hydroxide, a strong base, and that is used in the making of sodium hypochloride, a bleach and something also used in clarifying water. Acids and bases can be strong or weak. Sulfuric acid here, or nitric acid, are strong acids. Sodium hydroxide is a strong base. We're much more used to encountering weak acids and bases in our home environment. For instance, vinegar and citric acid are weak acids; ammonia is a weak base.

Shots of chemical plant

NARRATOR (NAT SOUND under):
Bases, the basis of household industry.

MONTAGE: Shots of household cleaners

MUSIC

MONTAGE: Household cleaners, ammonia plants, farm machinery, construction equipment, lime, sewage treatment plant, river, furnace, smokestacks

NARRATOR (MUSIC and NAT SOUND under):
Bases, the opposite of acids, neutralize them. They react with acids. In industry, these acid-base reactions are very important. Ammonia reacts with acids like phosphoric acid to produce fertilizers. The U.S. produces 70 million tons of fertilizer a year, one-fifth of the world's production. This base ranks fifth on the list of most produced chemicals, it's lime. If farmers want to neutralize excess acids in soil, they use lime. Like ammonia, lime cleans up. It's used to precipitate impurities from sewage. If left untreated, the sewage would carry harmful nitrogen and phosphorus compounds back into water. Lime is one chemical to be dumped. (cont.)

NARRATOR cont:
Dumped into rivers like this one in coal-mining country, it will reduce acidity, and dumped into coal-burning power plants, it can neutralize 90 percent of the acidic pollutants that could escape into our atmosphere.

MONTAGE: Chemical reactions, people drinking, plants, fruits, vinegar, fermenter, corn field, orange juice

NARRATOR (MUSIC and NAT SOUND under):
Acids. Strong acids are essential in industry as reactants and catalysts. They're not chemicals for everyday contact. Far too potent are concentrated nitric, hydrochloric, and sulfuric acid that can dissolve metals. Yet weak acids we know well. Citric acid is a weak acid and it's found in many beverages and in plants, and, of course, in citrus fruits. Apples are a natural source of another weak acid, acetic acid, found in vinegar. Such acids not only occur in the natural world. They can also be manufactured. In this fermenter, microorganisms produce citric acid from the raw material, corn starch. So, acids in your drink? Certainly, when they're like citric acid, weak and dilute. Acids and bases, then, vary widely in their properties, as Dr. Donald Showalter is discovering.

DS in lab

DON SHOWALTER (SYNC):
Yuck! Have you ever had a sip of wine that reminded you of vinegar? Or how about taking a bite of a fresh lemon? Boy, is that sour? Both of these are very sour. Now, that's a sure indication of having too much acid. In the kitchen now we can tell if something is acidic by its sour taste, but in the laboratory we don't taste, we test. Let's do a little bit of an experiment. What I'd like to do is to take this piece of blue litmus paper and add to it a little bit of that lemon juice. And watch what happens. The litmus paper turns red. Now, that's an indication of an acid. Now let me help you remember that: blue to red, ac-id. Now let's do our test with this common laboratory acid. Put a little of the acid into this dish. I'm going to put some of it onto this litmus paper, just like we did before. Now watch what happens.

EQUATION

Again, the litmus paper turns red, indicating an acid. Now let's do another experiment with this laboratory acid. What I'm gonna do is pour some of it into this test tube. All right. I'm going to add some magnesium ribbon to it. Let's see what happens. Look at the bubbles being formed. The magnesium reacts with the acid to give off a gas. Pretty neat, huh? All right. Let's try another substance with this acid. (cont.)

DON SHOWALTER cont:
This is limestone. I'm gonna add some of that into this test tube, and let's see what happens when we put a little acid in there. Notice the bubbles. The acid is reacting with the limestone and giving off a gas. Okay. Now that we have seen some acid reactions, I know just what you're wondering. What will bases do with the same substances? Well, let's try it and see. I've got some ammonia, which you know is a base. We'll pour a little bit of that into this glass, and let's test that with some blue litmus paper. Well, you see that it gets a little wet, but it really doesn't have a color change. What if we would try red litmus paper? Here's a piece of red litmus. Wow, look at it. As you see, it turned blue.

EQUATION

So the red litmus paper turns blue, an indication of a base, red to blue. Let's take some of that same base, some of this ammonia, put it into this test tube, and see if it reacts with this, the magnesium. Remember that? Put it in there and presto -- nothing happens. Now, what about if I poured some of this ammonia again into this limestone. Remember the limestone? What's gonna happen over there? What do you think? Nothing. Absolutely nothing. Now, what does that mean to us? It means that bases do not react with magnesium or with limestone.

Lab demonstration

NARRATOR:
Acids and bases change the color of dyes such as litmus. Acids produce hydrogen gas when reacting with metals such as magnesium. Acids produce gaseous carbon dioxide when reacting with limestone. Bases do not react with magnesium or limestone. Acids and bases are opposites. They react to neutralize each other.

DS in lab

DON SHOWALTER (SYNC):
What would happen if we mixed acids and bases? Let's try this one. I'm just gonna take these tops off, put the tops together. Look at the smoke. Definitely a reaction, huh? How about this pair? There's nothing exciting there. I don't see anything happening. How about this pair? Wow! Look at the bubbles. Now, those three reactions certainly were different. But what do you think these reactions have in common?

GRAPHIC: Acid-base reactions

NARRATOR (MUSIC under):
The ammonia and the hydrogen chloride react to form a cloud of solid ammonium chloride. Nitric acid reacts with sodium hydroxide to form soluble sodium nitrate and water. (cont.)

NARRATOR cont:
Acetic acid reacts with sodium bicarbonate to form carbon dioxide gas, water, and soluble sodium acetate. So what do these reactions have in common? To find out, consider the language of chemistry. The reactions still appear different, but look closer. In all three, hydrogen plays a role. A transfer of hydrogen is the common factor, and it can be visualized more clearly on the molecular level. Focus on a single molecule of hydrogen chloride and a molecule of ammonia. Here hydrogen chloride acts as an acid, donating a proton. Ammonia acts as a base, accepting a proton. A proton was transferred.

Farm machinery

NARRATOR (MUSIC and NAT SOUND under):
Proton transfer is the key process in the manufacture of fertilizers.

EQUATION over chemical plant shots

NARRATOR (MUSIC and NAT SOUND under):
Ammonia is reacted with phosphoric acid, accepting a proton, to produce ammonium phosphate, for example.

MONTAGE: Plant shots, phosphate rock, rock being crushed, limestone, smokestacks, furnaces

NARRATOR (MUSIC and NAT SOUND under):
Another way of getting essential nutrients to the soil is to use phosphate rock as a starting point. Sulfuric acid transfers a proton in this reaction, which produces super phosphate. In industry generally, sulfuric acid is used as a catalyst because of its superior proton-donating properties. Another acid-base reaction is now being employed in coal-burning power plants. It has led to a new useful limestone, a base. In the furnace of this power plant, coal is crushed and fluidized. It has been burned in a bed of limestone. Sulfur dioxide from the coal is neutralized and remains in the ash. Why could fluidized bed combustion be so important? Because the pollutants that have usually gone up in smoke are a cause of acid deposition, or, as it is more commonly known, acid rain. Dr. John Malanchuk, of the Environmental Protection Agency.

INTERVIEW: Dr. John Malanchuk, Environmental Protection Agency

SUPER: John Malanchuk

DR. JOHN MALANCHUK (SYNC):
Most acid rain is produced by humans, mainly from two major sources, stationary sources and mobile sources. Stationary sources are exemplified by power plants, electrical generating power plants, which burn coal or fuel oil and emit sulfur dioxide into the atmosphere, which combines with water vapor and forms acid rain, just as it occurs naturally. Mobile sources are actually cars, trains, planes, et cetera, internal combustion engines which burn gasoline and produce mainly oxides of nitrogen, which are emitted into the atmosphere in the same process, combine with water vapor and produce acid rain.

MONTAGE: Forest fires, factories, forests, plants, rain run-off, underwater shots, monuments, buildings, cars, lakes, sampling lakes, dead fish

NARRATOR (MUSIC and NAT SOUND under):
Acid rain can also be caused naturally, by forest fires, for example. But as both humans and nature cause the pollution, so are they affected by it. (cont.)

NARRATOR cont:
Midwestern oaks, maples in the Northeast, the proud ponderosa, all are damaged, nutrients destroyed, leaves and needles lost, shoots appear crooked, deformed, leaves turn out discolored and abnormally small. According to the National Wildlife Federation, one storm in Wheeling, West Virginia, had the acidity of auto battery acid.
Monuments, buildings, even the paint on cars can become pitted and discolored from the effects of acid rain. In the Western states, nitrogen oxides are thought to be mainly responsible for the change in the rain. In the East, it's sulfur dioxide transformed into dilute sulfuric that's primarily responsible.
Lakes of the Northeast and elsewhere are now the focus of scientific study. Fish and underwater life are threatened. The Environmental Protection Agency is investigating some 3,000 lakes in all. Samples of the water must be taken and rapidly analyzed in mobile laboratories. Some lakes are able to absorb changes in acidity quite well. Other lakes become much more acidic, sometimes irreversibly, such that the damage to life is severe. In other words, acid rain can lead to a range of acidity in lake water. There is a significant principle here. Generally, when it comes to measuring acidity, more acidity, less acidity, the role of water is crucial.

RH in office with chemical models

ROALD HOFFMANN (SYNC):
Water is by far the most common medium in which acids and bases exist and act. What would happen in the molecular world if we were to take an acid, for instance HCl here, and to put it into water? It would immediately transfer a proton to the water molecule, to give a hydronium ion, H3O+. The water is here acting as a base, accepting a proton. On the other hand, if we were to take a base, ammonia, into water, what happens then is that the water gives up a proton to the ammonia, leaving behind a hydroxide ion, OH-minus. Water, in this case, is acting as an acid, a proton donor. The very same substance, water, in one case an acid, in the other case a base. And would there be any proton transfer in water by itself in the absence of any added external acid or base?

GRAPHIC: The hydronium ion in water

NARRATOR (MUSIC under):
Only one water molecule in 500 million accepts a proton. That molecule becomes hydronium ion. The water molecule that lost the proton becomes a hydroxide ion. Chemically speaking, an equilibrium exists among the hydroxide and hydronium ions and water molecules. (cont.)

NARRATOR cont:
Still only one out of 500 million molecules of water becomes a hydronium ion. This corresponds to 10 to the minus-7 moles of hydronium ion per liter.

RH at chalkboard

ROALD HOFFMANN (SYNC):
We've seen that in water itself, there is a tiny amount of hydronium ion in solution. What if we were to add to that water an acid, for instance, hydrochloric acid? That acid would transfer its proton to the water, like a shot, to generate some hydronium ion and there would be much more of that hydronium ion from the acid than there would be from the water equilibrium itself. And if instead of a strong acid, we were to add a weak acid, say acetic acid, that's what CH3COOH is, that weak acid would also transfer a proton, this one, to the water solution to give hydronium ions, but it would do so much less effectively than the strong acid HCl. The number of hydronium ions in the solution of a weak acid is much less than those in a solution of a strong acid. Both of them are bigger than they would be in the water equilibrium itself. We've seen that in a solution of a strong acid, such as hydrochloric, there are many more hydronium ions in solution than there are in the case of a weak acid. (cont.)

ROALD HOFFMANN cont:
The actual range of concentrations of hydronium ions that we normally encounter in chemistry is incredibly large, over 14 powers of 10, 14 orders of magnitude. We need an instrument to measure this incredibly large range of hydronium ion concentrations.

DS in lab

DON SHOWALTER (SYNC):
It's a pH meter. It works on the principle of an electrochemical cell. It consists now of this meter that gives us a number readout, and this electrode which measures the concentration of hydronium ion in solution.

EQUATIONS over lab demo

NARRATOR:
We have to devise a convenient way of representing the range of acidity in water solution. For this we can use a comparatively simple relationship, that the hydronium ion concentration in water equals 10 to the minus-something. That something is going to be what we call the pH. For example, here is a range of solutions of differing acidity. When the concentration of hydronium ion is 10 to the minus-1, the pH will be 1. When the concentration of hydronium ion is 10 to the minus-2, the pH will be 2. (cont.)

NARRATOR cont:
When the concentration drops to 10 to the minus-7, the pH will be 7. And this is the pH of pure water. pH 7 is the dividing line between acids and bases. The value of the pH becomes larger than 7 when the hydronium ion concentration gets even smaller.

DS in lab

DON SHOWALTER (SYNC):
Here we have a chart that shows the pH scale. And as my laboratory assistant will point out, the pH of bleach is just under 13, the pH of milk of magnesia just above 10. Sea water is just below 9. Blood is right at 7.4. And pure water at 7.0. Black coffee about 5. Vinegar just under 3. And then there are stomach fluids.

Archival stomach footage

NARRATOR (MUSIC under):
pH 1. Even in the normal stomach, the acid is hydrochloric acid. An expert on stomach acid is Dr. Paul Maton of the National Institutes of Health.

INTERVIEW: Dr. Paul Maton, National Institutes of Health

SUPER: Paul Maton

DR. PAUL MATON (SYNC):
The stomach produces a small amount of acid all the time, but then that amount of acid may be stimulated by food. Even the sight and smell of appetizing food is enough to make the stomach produce more acid.

GRAPHIC, antacid solution and tablets

NARRATOR (MUSIC under):
What actually happens when you eat a meal? Both hydrogen ions and chloride ions, maintaining an electrochemical balance, move through the stomach lining from the surrounding blood plasma. In the stomach the result is a highly acidic medium. That's what it takes to activate certain enzymes for the process of digestion. If the acidity of the stomach becomes excessive, problems can occur, problems which often need antacid solutions.

INTERVIEW: Dr. Paul Maton cont.

DR. PAUL MATON (SYNC):
There are a variety of different compounds that can function as antacids. For example, sodium bicarbonate could be used as an antacid, or magnesium hydroxide, calcium carbonate. There are a variety of compounds.

Antacid solution

NARRATOR (NAT SOUND under):
Basically bases, once more the basis of another household industry.

Alkaseltzer commercial

Rolaids commercial

Tums commercial

INTERVIEW: Dr. Paul Maton cont.

DR. PAUL MATON (SYNC/VO):
All antacids neutralize acid. And if they're given in sufficient amount, any antacid is as good as another at neutralizing acid.

People on street, graphic of stomach

One hears a lot of talk about hyperacidity and too much acid. In fact, there's very little or no evidence that people with ulcers actually produce more acid than many of the rest of us.

Archival footage of antacid solutions

NARRATOR (MUSIC under):
For most of those acid stomach discomforts, then, the tried and tested over-the-counter remedies do their job of neutralization well enough.

SUPER: THE PROTON IN CHEMISTRY

MONTAGE: Lab demonstrations, program graphics, water, equations

NARRATOR (MUSIC under):
To review: In the laboratory, acids are recognized by their ability to change the color of dyes, turning litmus red, for example. They react with metals, like magnesium, to produce hydrogen. Acids and bases react together. Today, acids and bases are defined in terms of hydrogen ion, or proton transfer. An acid donates a proton to a base. A base accepts a proton from an acid. Water is the most important medium in which acids and bases act. The difference between a strong acid and a weak one is the concentration of hydronium ions in solution. In aqueous solution, that concentration of hydronium ions ranges over 14 powers of 10. A strongly basic solution has a pH of 14, and a strongly acidic solution has a pH near zero. (cont.)

NARRATOR cont:
As the hydronium ion concentration increases, the pH number decreases. Pure water has a pH of 7, the dividing line between acids and bases.

RH at chemical plant

ROALD HOFFMANN (SYNC):
Proton transfer is not just essential business in the molecular world of the chemist. It's really big business. Remember that list of the ten top chemicals, five of which were acids and bases? Someone is making them in tens of billions of kilograms. They're not doing it just for fun. Someone else is buying those molecules. And, in turn, they are being transformed into all the consumer goods around us. Actually, that transformation bears thinking about. Strong corrosive acids are being changed into molecules that are neither acid nor corrosive, nor in any danger of regenerating the acid from which they were made. Does that surprise you? It really shouldn't. Molecules are a thing unto themselves, independent of the history of their production. All that matters in giving a molecule its properties are its component atoms and the way they are arranged in space, the way they are connected to each other. (cont.)

ROALD HOFFMANN cont:
Let me give you an example, nitric acid, HNO3, is a strong acid, but its component elements, hydrogen, nitrogen, and oxygen are not acid at all. So please don't worry that the bagel that you eat, for instance, which was made from wheat that was grown using a fertilizer, ammonium nitrate, that, in turn was made from nitric acid, that that bagel will spontaneously revert to nitric acid to burn you. It won't.

Credits, Closing Montage, Closing Music

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